TRANSIENT ANALYSIS OF X-34 PRESSURIZATION SYSTEM

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ABSTRACT

Two transient operational modes of the X-34 pressurization system were analyzed using the ROCket Engine Transition Simulation (ROCETS) program. The first operational mode considers the normal operation. For the engine burn period, the required helium mass and pressure of each propellant tank were calculated. In the second case, the possibility of failure of the pressurization system solenoid valves, its consequence on the over-pressurization, and simultaneous operation of pressurization and vent/relief systems were evaluated.

INTRODUCTION

The X-34 technology development program is a joint industry/government project to develop, test, and operate a small, fully-reusable hypersonic flight vehicle demonstrating technologies and operating concepts applicable to future Reusable Launch Vehicle (RLV) systems. The X-34 Main Propulsion System (MPS) stores and delivers Rocket Propellant 1 (RP-1) fuel and Liquid Oxygen (LOX) oxidizer as required by the NASA-MSFC Fastrac engine. The MPS consists of the Tank Pressurization Subsystem, Pneumatic and Purge Subsystem, Propellant Feedline Subsystems, and Fill/Drain/Dump Subsystems. An overview description of the X-34 MPS has been provided by Sgarlata and Winters[1]. The detailed descriptions of the feed subsystem and propellant management, and pressurization subsystem are provided by McDonald et. al[2] and Brown et. at[3], Hedayat, et. al[4], respectively.

Stored-gas pressurization systems are used to transfer propellants from the tanks to the turbopump at the needed flow rates and pressures. In the pressurization systems, helium is commonly used because of its lower molecular weight and thus reduced total pressurant weight Gaseous Helium (GHe) is stored in bottles at high pressure, then it is supplied to the propellant tanks at limited flowrates using valves, regulators, and orifices. In addition, solenoid valves control the pressurization of the LOX and RP-1 tanks within an allowable pressure range.

In the event of a pressurization system solenoid valve failure (fail open scenario), the propellant tank is over-pressurized. The over-pressurization can result in structural failure of the propellant tanks. A vent/relief system on the propellant tank is intended to relieve the ullage without allowing the tank pressure to rise above proof. In the solenoid valve failure scenario, the vent/relief valves must be capable of opening fast enough to establish the relief flow prior to the tank pressure reaching proof. In this analysis, only the RP-1 tank is considered due to its very low initial ullage volume.

Using ROCETS[5], two operational scenarios for the pressurization system were simulated. In the first case, normal operation of the pressurization system helium usage and thermodynamic conditions were evaluated. The second case deals with the simultaneous operation of pressurization and vent/relief systems and maximum ullage pressure within RP-1 tank is calculated.

ANALYSIS

System Description

A schematic of pressurization and vent/relief systems is shown in Figure 1. Helium is supplied to the propellant tanks through two regulators. During the pressurization process, the second regulator is considered to be completely open while the passage of the first regulator is adjusted such that the pressure at the exit is maintained at 350 psi. The helium pressurant is stored initially at 5000 psia and 530 °R. The allowable pressure range for the LOX and RP-1 tanks are 55-61 psia and 47-53 psia, respectively. A closed loop control circuit uses tank pressure sensor output to control opening/closing of the flow control solenoid valves, thus maintaining tank pressure within the above control band as propellant is expelled from the tanks.

In the event of a pressurization system failure, the vent valve must respond fast enough to prevent tank pressures from rising above their proof ratings. If the solenoid valves fail open, the continuous flow of helium and its accumulation in the tank leads to the pressure build-up and eventually over-pressurization of the RP-1 tank. As the pressure reaches a specified value, the relief/vent valve is opened to allow ullage to leave, therefore relieving the pressure. The over-pressurization magnitude depends on the vent/relief valve response time. In this analysis, for the vent/relief valve, a response time range of 0.5 to 1.0 second is considered. In addition, the following assumptions are made:

1. Helium initial temperature and pressure are 530 °R and 5000 psia.
2. LOX temperature is 163 °R.
3. RP-1 line has an ID of 0.65″ (OD = 0.75″), and the rest of the system has an ID of 0.83″ (OD = 1″).
4. Densities of LOX and RP-1 at described conditions are 71.5 lbm/ft^3 and 50.5 lbm/ft^3, respectively.
5. Volume of LOX and RP-1 tanks are 300 ft^3 and 188.51 ft^3, respectively.
6. Start transient flowrates data for the first 2.5 seconds from reference[6].
7. LOX tank initial ullage volume is 19.6 ft^3.
8. The 2.5'' Vent/Relief valve has a relief capacity that of a 1.5" equivalent sharp-edged orifice diameter with a discharge coefficient of 0.60. In addition, the vent have a capacity of 2.5" equivalent sharp-edged orifice diameter with a discharge coefficient of 0.60.
9. Considering V' = volume flowrate, m' = mass flow rate, ρ = density, and $V' = m'/\rho$, engine requirements during the steady state engine operating period are as follows[7]:

Fluid	m' (lbm/sec)	V' (ft^3/sec)
LOX	144.0	2.014
RP-1	66.0	1.307

In the analyses, the ROCETS models were run for 3 different initial RP-1 tank ullage volumes of 0.5% (0.94 ft^3), 1.0% (1.88 ft^3), and 1.5% (2.82 ft^3) of the RP-1 tank volume. Also, the ROCETS model contained the pressurization model as described in Hedayat, et. al.[4]. When the RP-1 tank reaches a 85 psia a delay equivalent to the vent/relief valve response time (0.5-1.0 second) is imposed, then the vent/relief valve is set to full open allowing the ullage to exit. As the helium discharges from the tank, the pressure within RP-1 tank drops. When the ullage pressure drops below 75 psia, the vent/relief valve is closed.

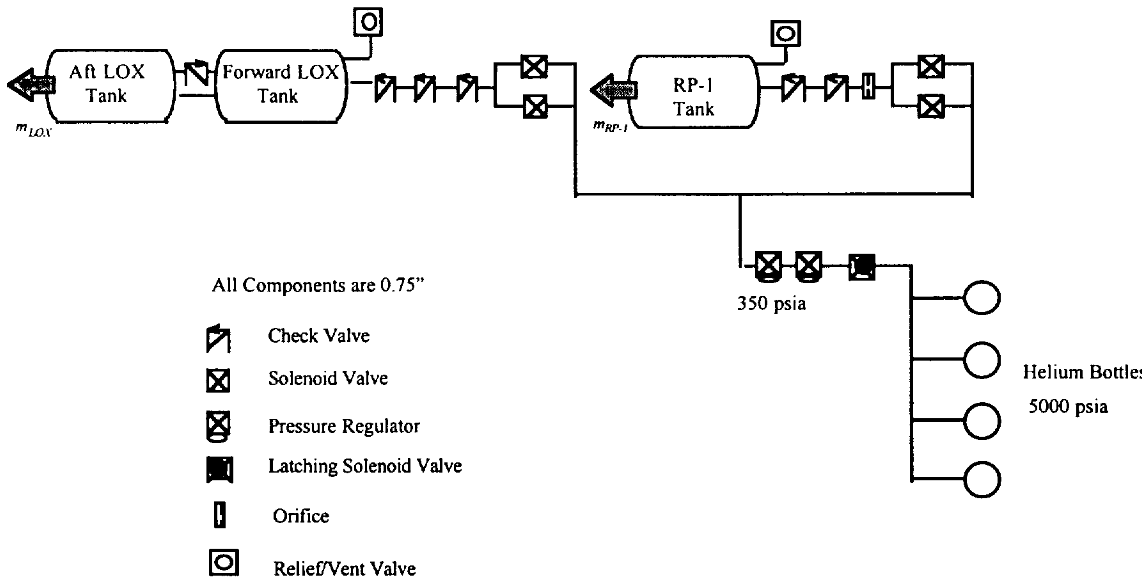

Figure 1. Pressurization and Vent Systems Schematics.

Results

In the ROCETS model, the delay from the instant tank ullage pressure reaches the specified set-point until a signal reaches the solenoid valve is considered to be 0.04 seconds. The additional delay due to the valve response to a signal is assumed to be 0.05 seconds. The valve closing/opening area variation is modeled linearly.

Figure 2 shows the pressure history of the ullage within the RP-1 tank. Initially, the ullage pressure is 53 psia. The ullage reaches a maximum of approximately 54.2 psia after 2.5 seconds. Figure 3 illustrates the RP-1 tank helium usage history. After 110 seconds, the RP-1 tank contains 7.58 lbm of helium. At this point, the solenoid valve is closed and the ullage mass is kept constant until the end of the engine burn. At the end of the pressurization process, the RP-1 tank ullage pressure is 39 psia.

The LOX ullage pressure history is shown in Figure 4. The LOX tank was maintained at 65 psia with a ±3 psi control range. The LOX ullage pressure reaches a maximum of 68.5 psia after 1.5 seconds. The LOX tank ullage mass history is depicted in Figure 5. This figure indicates that at the end of pressurization process, the LOX tank contains 44 lbm of helium.

Figures 5 and 6 show the RP-1 tank ullage pressure history for the pressurization system solenoid valve failure scenario. Figure 6 illustrates the RP-1 tank ullage pressure history for a vent/relief valve response time of 1 second. For 0.5%, 1.0%, and 1.5% initial ullage volumes, the maximum ullage pressures are 190 psia, 118 psia, and 89 psia, respectively. For a response time of 0.5 second, Figure 7 indicates that the maximum ullage pressure for the 0.5%, 1.0%, and 1.5%, initial ullage volumes are 142 psia, 110 psia, and 80 psia, respectively.

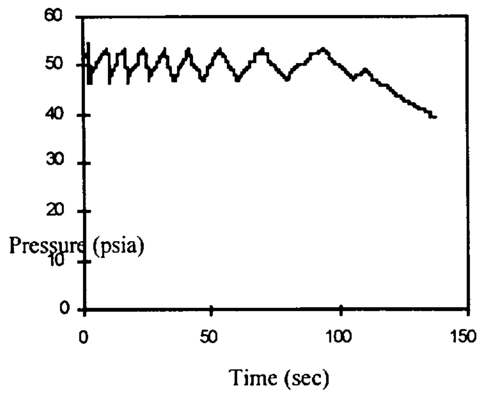

Figure 2. RP-1 Tank Ullage Pressure History.

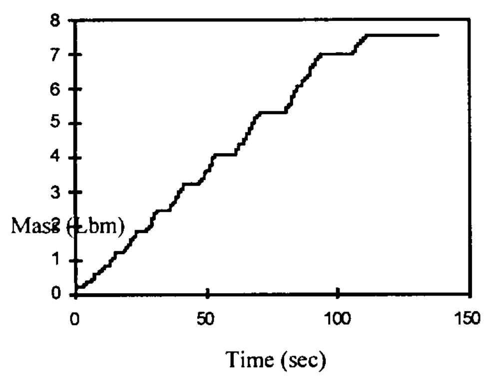

Figure 3. RP-1 Tank Ullage Mass History.

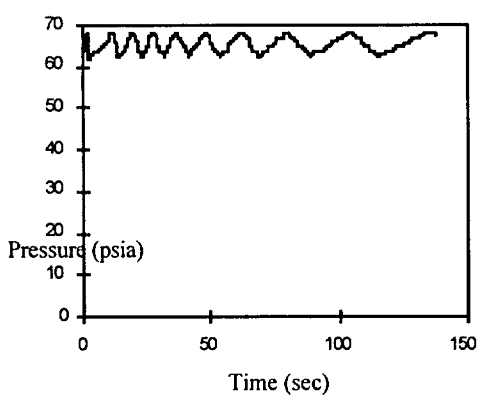

Figure 4. LOX Tank Ullage Pressure History.

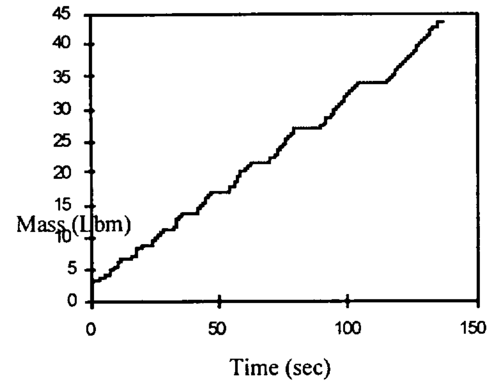

Figure 5. LOX Tank Ullage Mass History.

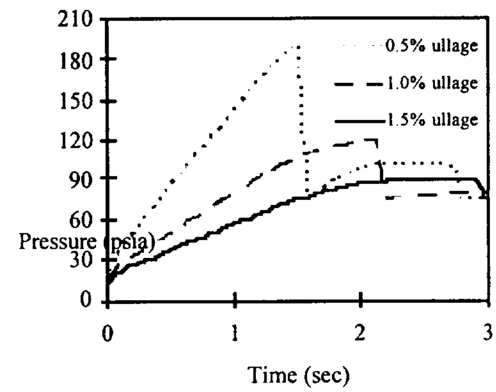

Figure 6. RP-1 Tank Ullage Pressure History for a Vent/Relief Response Time of 1.0 second.

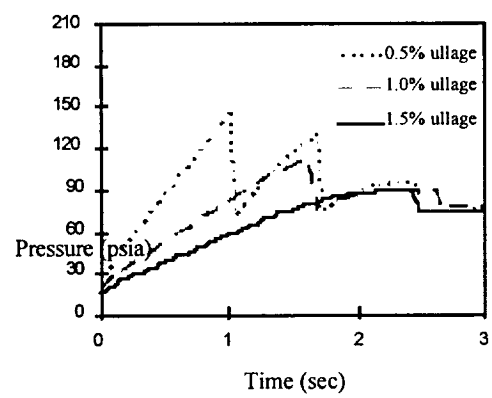

Figure 7. RP-1 Tank Ullage Pressure History for a Vent/Relief Response Time of 0.5 second.

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